

# Stay by thy neighbor? Structure formation, coordination and costs in tradable permit markets with spatial trading rules

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## Abstract

Market-based instruments have been proposed as a means of implementing cost-effective and adaptive policies for biodiversity conservation. Their very foundation is a well-defined measure of ecological value; only the latter makes conservation services comparable and translates them into a commodity which can be traded among market participants. But what is the right value when local conservation decisions affect ecological functions on a larger scale and thus create spatial externalities (site synergies) on neighboring sites? By means of an agent-based model, we analyze different spatial trading rules and their implications on land use decisions in a dynamic cost environment. The model contains a number of alternative submodels which differ in the individual assignment of market values and in the social organization of agents, the latter including cheap talk coordination and cooperation. We show that spatially explicit trading rules can effectively adapt land use towards species requirements and individual costs. For a certain class of submodels (local decisions), we find thresholds for the effectiveness of spatial incentives along a curve of critical parameter values. The progression of this curve is derived analytically and shown to agree with the simulation results. Further, we show that cases of low social organization (e.g. no communication) are particularly prone to suboptimal land allocations due to misinformation and coordination failure.

*Key words:* land use, spatial externalities, tradable permits, biodiversity conservation, agent based models, social interactions

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## 1. Introduction

What is the value of nature? Markets for biodiversity conservation are based on the possibility of determining standards which rate conservation services (e.g. the provision of an acre of rainforest) in terms of their contribution to conservation targets. However, when ecological processes operate at much larger scales than typical landowner properties, local land use decisions are likely to produce side effects on the ecological value of neighboring land. This paper deals with the problem of including such spatial interactions into the market values of conservation measures.

Markets are not a new choice, but still a rare one for biodiversity conservation policies. Traditionally, conservation practice and research have been dominated by static planning, offering a fast response to the growing environmental problems encompassing the progress of industrialization in

the last century. At present, systematic conservation planning may include ecological interactions, external drivers and socio-economic conditions (Margules and Pressey, 2000) and is undoubtedly the cornerstone of ongoing conservation efforts. A particularly important factor for the effectiveness of conservation planning is the inclusion of local conservation costs (Faith and Walker, 1996; Ando et al., 1998). Unfortunately, this insight also points to a practical problem of planning approaches: Local costs are frequently difficult or expensive to estimate, they may change over time, and it is seldom in the interest of landowners to report them honestly. In these cases, market instruments such as auctions, contracts or tradable permits provide an alternative to planning approaches because they are able to efficiently allocate conservation efforts, even at no information about local costs (information asymmetry).

The common denominator of market instruments is to introduce a measure (e.g. based on habitat quality, size) which rates the value of local sites or services in terms of their contribution to conservation targets. This measure translates conservation efforts into a commodity which

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may be offered on the market (Wu and Babcock, 1996; Latacz-Lohmann and Van der Hamsvoort, 1998; Wunder, 2007). The balance of demand and supply automatically extracts local conservation costs and leads to a cost-effective allocation of conservation efforts as long as the market is competitive.

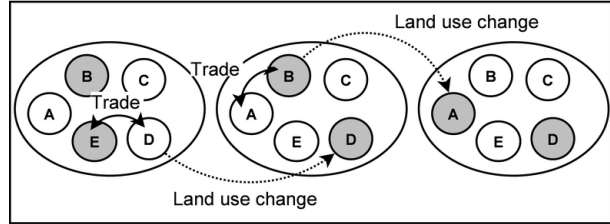
Yet, while markets solve the problem of cost information asymmetry, the definition of an accurate measure of conservation value runs into problems when ecological values of local sites are spatially or temporally correlated, as it is frequently the case for habitat networks (Opdam et al., 2006). An apparent solution is to incorporate spatial dependencies into market values. While this is generally possible, it implies that conservation decisions may change the market value of neighboring land. In the presence of such spatial interactions, referred to as externalities by the economic literature, trading might lead to inefficient outcomes if no correction is introduced (Mills, 1980). Moreover, ecological processes may operate on a large range of spatial and temporal scales and show complex dependencies, making such corrections possibly very difficult. Moilanen (2005) for example discusses a case where static optimization is already computationally hard. It is therefore not clear a priori if market participants will be able to find their optimal allocation, in particular if they are subject to external drivers such as changing conservation costs. In a sense, we may view the process of trading conservation services as a self-organized reserve site selection algorithm (Faith et al., 2003). The aim of our analysis is to find out under which market rules this algorithm is successful in finding good solutions to the allocation problem of interacting sites, and under which conditions it may fail.

## 2. Problem setting, tradable permits and modeling approach

In this paper, we consider a tradable permit market as an example of a market for conservation services. Such a market is initiated by distributing conservation obligations among landowners, adding up to the desired regional level of conservation. Every landowner who undertakes conservation receives a certificate which documents the value of his contribution. Landowners who hold obligations can either choose to undertake conservation measures according to their obligation, or buy certificates from other landowners whose amount of certificates exceeds their obligation. Ideally, subsequent trading among market participants leads to a socially optimal allocation of conservation measures across space and time while trading rules ensure that the conservation target is fulfilled at any time. Fig. 1a shows a typical trading procedure in this kind of market.

Translating the problem of spatial interactions to the context of a tradable permit market, we would like to know:

a) Trading procedure



b) Spin model of local interactions

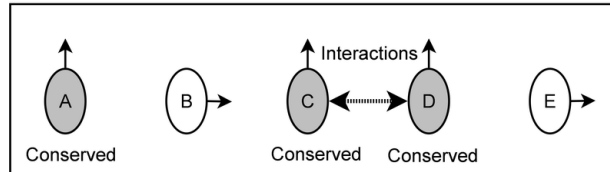


Fig. 1. a) Tradable permit market - Initially, sites B and E are conserved. E pays D to take over his conservation obligation. In the next step, D starts conserving his land and E can withdraw from conservation. This is repeated in the next step for A and B. We assumed here that all sites have equal value and that land use can be changed immediately. b) Spin model of local interactions: Conserved sites in direct vicinity interact with each other, leading to a higher ecological value than isolated sites.

What is the right (certificate) value for a local site which interacts with other sites through a habitat network? Our approach to answer this question is based on the following three pillars:

*"The total amount of certificates must always reflect the global ecological value":* Certificate trading rules must be chosen such that, starting from an arbitrary configuration, trading can only lead to a configuration of equal or higher value. This is ensured when the total amount of certificates always accurately reflects the total ecological value.

*"The individual assignment of certificates can be varied. The best choice is the one which realizes the desired level of conservation at lowest costs":* Respecting the first rule, there might still be several ways to distribute the total amount of certificates among local landowners. The individual assignment should be chosen to maximize the cost-effectiveness of the land allocation emerging from trading.

*"Different social structures might affect the optimal choice of assignment rules":* As landowners' decisions are mutually dependent, aspects such as communication may play an important role for individual decision making. Different social organization structures may suggest different individual assignment rules, even if the ecological situation is the same. Fig. 2 illustrates how we translated these questions into our simulation. In the rest of this section, we will give a non-technical motivation for the chosen submodels.

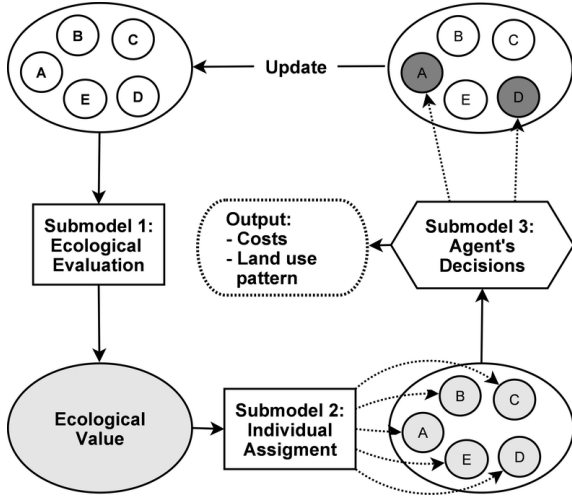


Fig. 2. Modeling approach: On the left the ecological evaluation, starting from a land configuration with local sites A-E and leading to an estimate of ecological value of the whole configuration. On the right the market, starting from certificate values for the sites A-E and leading to a changed land configuration. Both sides are connected by the individual assignment.

### 2.1. Submodel 1: Ecological evaluation

The survival of species in fragmented, dynamic landscapes is subject to a complicated interplay of reproduction, dispersal and mutual interaction. To estimate the value of such landscapes, we need to define categories in which we rate them. These categories are by their nature normative and subject to the current understanding of ecosystem functions and societal preferences. An extensive amount of literature deals with this question, e.g. (Saunders et al., 1991; Frank and Wissel, 1998; Opdam et al., 2003; Bruggeman et al., 2005). Here, it is widely agreed that habitat connectivity is a key factor for the viability of a large range of species. For our simulation, we will make a crude simplification: We assume connectivity and area are the only important factors for the ecological value of a site. More explicitly, we assume that  $N$  sites of unit size, assembled to a network, have an ecological value of

$$\hat{U} = \sum_i^N \{(1 - m) + m \cdot \beta_i\} \quad (1)$$

where  $\beta_i$  is a parameter measuring the connectivity of the  $i$ -th site, while  $m$ , taking values from 0 to 1, measures how much the species under consideration values habitat connectivity over area. Despite its simplicity, this function reflects the importance of area and connectivity as an essential insight from spatial ecology. Qualitatively, our results can be expected also to hold true for more complex evaluation functions such as the one derived by Frank and Wissel (2002).

### 2.2. Submodel 2: Individual assignment

Having defined a value  $\hat{U}$  for any landscape configuration, we now ask: How should  $\hat{U}$  be split up among local sites? We consider two submodels which distribute the same total amount of certificates, but differ in the individual assignment of certificates among agents:

*Additive certificate values* (1): A straightforward way is distributing any gain in  $\hat{U}$  that results from mutual benefits of neighboring sites among the neighbors involved (See Fig. 3). The proportion assigned to each landowner should reflect the contribution of his land to the ecological value of neighboring sites. It is easier to assume that mutual benefits are symmetric between sites, but the non-symmetric case (see Vuilleumier and Possingham, 2006) can equally be treated. In the context of payment schemes, a similar rule has been proposed by Parkhurst et al. (2002). We call this option "additive certificates" because the value of all distributed certificates adds up to the global value and the value of any subset of sites is the sum of its certificate values.

$$\sum_i \hat{b}_i = \hat{U} \quad (2)$$

*Marginal certificate values* (2): For the second option, we set the certificate value of a site  $i$  equal to the marginal change of global value resulting from a change at this site while all other sites remain as they were:

$$\Delta_i \hat{U} \equiv \hat{U}^{\text{new } i} - \hat{U}^{\text{old } i}. \quad (3)$$

Unlike additive certificates, the marginal rule assigns all costs and benefits created by a land use change to its originator. Yet, while such a situation is generally favored by economic theory, practically this is connected with considerable complications: Unlike additive certificates, marginal values are in general not additive. This means that the marginal value of 2 sites is not generally the sum of the two sites' marginal values. Further, the resulting payoffs for landowners depend on the order of trading. This does not pose theoretical problems, but it might lead to severe acceptance problems among landowners. Both properties are illustrated in Fig. 3.

### 2.3. Submodel 3: Social Organization

Clearly, if certificate values of a site depend on the neighboring sites, it is important for landowners to know their neighbors' intentions. But how much does social organization affect the results of the simulation? We assume that agents are always profit maximizing and myopic in the sense that they base their decision on the best action for the next timestep without displaying strategic behavior. Within this setting, we consider three behavioral submodels:

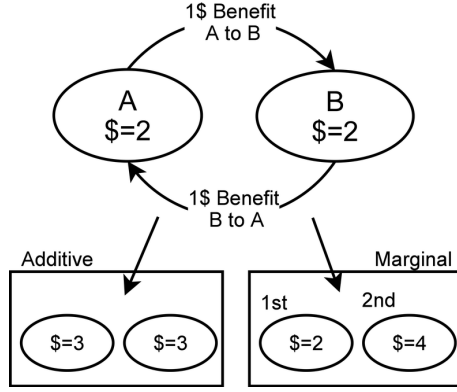


Fig. 3. Two sites A and B of equal size pose a mutual benefit to each other. When isolated, both sites have an ecological value of 2 each. Connecting the two sites creates an additional value of 2, resulting from a benefit of 1 in each direction. Given additive certificate values, each landowner receives 3. The marginal value of a conserved site in the absence of any other site is only 2, while the second site adds all mutual benefits and thus receives 4 – the order of creation matters.

*Null model (a):* In the null model, agents observe the present landscape configuration and decide in the prospect of the future land configuration being the same as the present one.

*Coordination (b):* It is natural to assume that agents will communicate their future intentions. This is beneficial because it increases the accuracy of the estimate about the upcoming land configuration. Coordination is understood by us as communication of non-binding information about the present state of the decision, often called cheap talk (Farrell and Rabin, 1996). Experimental studies have shown that the possibility of coordination by cheap talk leads to an increased probability of finding cost-effective configurations (Parkhurst et al., 2002). In general, cheap talk also offers the possibility of strategic lies. This option is omitted in the simulation and hence agents will always stick to the action they communicated as long as conditions do not change.

*Cooperation (c):* Further payoff improvements are possible if agents did not only coordinate, but cooperate. Cooperation means that conservation is provided if it is beneficial for the group, even when it is not in the immediate interest of the individual. In such a system, agents would reveal their true costs to the group, the best configuration would be chosen, and the payoffs would be distributed among the group members. However, this creates the temptation to communicate higher than the true costs to increase the individual share of the group benefits. Cooperation is a public good game and cooperators have to fear exploitation by defectors and free-riders. We will address this issue in detail in the discussion.

For the first two options a) and b), decisions are made locally, while cooperating agents c) decide on a global level. We will see later that these structurally different decision processes also reflects in the resulting land use pattern.

Table 1 summarizes the discussed model options and their properties. For cooperation, there is no difference between the two certification processes, because these differ only in the individual assignment of certificates, but not in the total assignment.

### 3. Model description

#### 3.1. Overview and purpose

To represent interactions between site values, we use a 2-dimensional spin model with local interactions (see Fig. 1b). Spin models have been used repeatedly in the literature to analyze phenomena of social interactions (Galam and Zucker, 2000; Sznajd-Weron and Sznajd, 2000; Holyst et al., 2000; Schweitzer et al., 2002). The model we present differs from a standard Ising model in two major points: Firstly, its dynamics are driven by a randomly fluctuating external field at each local site, representing changing conservation costs. Secondly, the system is constrained by the conservation target. To our knowledge, there has been no systematic analysis of this model in the literature, although it exhibits similarities to the Random Field Ising Model (Imry and Ma, 1975) and non-equilibrium models such as Hausmann and Rujan (1997) and Acharyya (1998). However, our focus is not to solve a somewhat modified Ising model. Instead, technically we are comparing different algorithms (specified by certification rules and agents' behavior) in terms of costs they require to reach the conservation target.

SYMBOL CONNOTATION		RANGE
$x_i$	i-th cell on the grid	
$\sigma_i$	State of the i-th cell $\{0, 1\}$	
$c_i(t)$	Costs of $\sigma_i = 1$ at t	$[1 - \delta \dots 1 + \delta]$
P	Market price	$[1 - \delta \dots 1 + \delta]$
$\delta$	Cost heterogeneity	$[0..1]$
m	Connectivity weight	$[0..1]$
$\lambda$	Ecological target	$[0..1]$

Table 2

List of state variables (top) and parameters (bottom)

#### 3.2. State variables and scales

The simulation is carried out on a 2-dimensional grid with 50x50 grid cells and periodic boundary conditions. We also refer to the  $N=2500$  grid cells as sites. Every grid cell  $x_i$  is owned by a different landowner (agent) and can be occupied with a habitat ( $\sigma_i = 1$ ) or be used for other purposes ( $\sigma_i = 0$ ). The occupancy of a grid cell results in conservation costs  $c_i(t)$  which have to be borne by its landowner. These costs are sampled at each time step from

LABEL	SUBMODEL	DECISIONS	GAME TYPE	Path	COMMUNICATION
(a.1)	Null additive	Local	1-player	independent	None
(a.2)	Null marginal			dependent	
(b.1)	Coordination additive		Coordination	independent	Intentions
(b.2)	Coordination marginal			dependent	
(c)	Cooperation	Global	Public Good	independent	Costs

Table 1

Overview of alternative submodels for the certification processes and agent behavior

a uniform distribution of mean 1 and width  $\delta$ . Following eq. 1, we assume that the conservational value of a landscape configuration, given by the values of  $(\sigma_1 \dots \sigma_N)$ , is

$$\hat{U} = (1 - m) \sum_{i=1}^N \sigma_i + \frac{m}{8} \sum_{i, <j>_i}^N \sigma_i \sigma_j \quad (4)$$

where  $<j>_i$  indicates all  $j$  which belong to the 8 cells  $x_j$  in a Moore neighborhood of  $x_i$  and  $m$  weights the importance of connectedness over area for the relevant species. The market is constrained by a conservation target

$$\hat{U} = \lambda \cdot N, \quad (5)$$

which is set by the parameter  $\lambda$ . Landowners demand certificates until they reach the target  $\lambda \cdot N$  and thereby create an equilibrium price  $P$  per unit value. A list of all basic state variables and parameters is given in Table 2. For convenience, we define the following abbreviations for the average number of occupied sites and the occupancy of the neighborhood of  $x_i$ , respectively:

$$\alpha \equiv \frac{1}{N} \sum_{i=1}^N \sigma_i, \quad \beta_i \equiv \frac{1}{8} \sum_{<j>_i}^N \sigma_j \quad (6)$$

Further, we define connectivity  $K$  as the average neighborhood occupancy  $\beta$  of the occupied sites

$$K \equiv \frac{1}{\alpha \cdot N} \sum_{i=1}^N \sigma_i \cdot \beta_i \quad (7)$$

and societal costs  $C$  of a landscape configuration as the sum of the costs of all conserved grid cells, divided by the number of grid cells.

$$C \equiv \frac{1}{N} \sum_{i=1}^N \sigma_i \cdot c_i \quad (8)$$

### 3.3. Process overview and scheduling:

At each time step, new costs  $c_i$  are sampled. Agents decide to maintain a site as habitat based on their costs  $c_i$ , the market price  $P$  and the estimated certificate value  $\tilde{b}_i$ . They maintain a habitat on  $x_i$  at timestep  $t$  if

$$\pi_i \equiv -c_i(t) + P \cdot \tilde{b}_i(t) > 0. \quad (9)$$

As discussed in section 2.2, we consider two certification options. Assuming symmetric benefits, eq. 4 results in additive certificate values of

$$b_i \equiv (1 - m) + m \cdot \beta_i. \quad (10)$$

The marginal certificate value of a site can be calculated from eq. 4 according to eq. 3:

$$b'_i \equiv (1 - m) + 2 \cdot \beta_i. \quad (11)$$

Although the process of certificate exchange is not modelled explicitly, the reader may assure himself that eqs. 10 and 11 do exactly create the decision base in terms of costs and benefits to match the trading rules described in section 2.2, in particular also the path-dependence of marginal certificates. The final benefits  $b_i$  rewarded at the end of the round can differ from the estimated benefits  $\tilde{b}_i$  because subsequent decisions by other agents can change the landscape configuration. The accuracy of the estimate  $\tilde{b}_i$  depends on agents' communication and organization abilities. The three submodels discussed in section 2.3 are implemented in the following way:

*Null model:* All agents decide in parallel according to eq. 9 without being informed about the decisions of other agents at this timestep.

*Coordination:* Agents decide sequentially in random order according to eq. 9. After each decision, all agents are informed about the new configuration. This procedure is repeated a number of times, mimicking the outcome of a non-binding exchange of information on the basis of willingness.

*Cooperation:* Cooperation is modeled by global optimization, which is described in the next subsection. It is assumed that all agents communicate their costs and decide together.

Step by step, the decisions of all agents are collected and the resulting ecological value  $\hat{U}$  as given in eq. 4 is calculated.  $\hat{U}$  is constrained by the conservation target of  $\lambda \cdot N$  (eq. 5). The emergence of an equilibrium between fixed demand (target constraint) and supply (eq. 9) is modeled by adjusting the market price  $P$  until the agents as a whole choose to conserve the target value  $\lambda \cdot N$  (Drechsler and Watzold, 2007). The order in which agents are asked is randomized at every timestep, but does not change while

the market price is adjusted. Fig. 4 shows a flow diagram of the processes within one timestep.

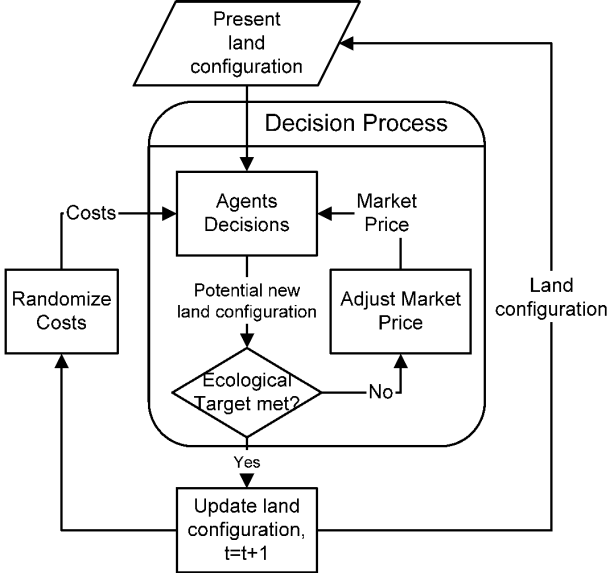


Fig. 4. Flow diagram of processes within one timestep.

### 3.4. Initialization and Stochasticity

Simulation runs were initialized with a random landscape configuration on the target level. A series of tests showed that the initial configuration has no influence whatsoever on the resulting landscape after a sufficient amount of time. This holds also true for non-random start configurations as well as random initial ecopoint levels. Data acquisition was started after 600 trading steps to ensure that the simulation had reached its steady state. The results show the mean of 50 runs. Standard deviations for all values were calculated but omitted for presentation because they were small and showed no significant information.

### 3.5. Optimization

To model a perfectly rational cooperating group of agents, we performed a global optimization of the land configuration. We used a slightly modified simulated annealing algorithm, which delivered better results than the original algorithm by Kirkpatrick et al. (1983). The goal of the optimization was to minimize the societal costs as defined in eq. 8 under the constraint of meeting the regulatory target as given in eq. 4:

$$\min \left\{ \sum_{i=1}^n \sigma_i \cdot c_i(t) \right\}_{\hat{U}=\lambda \cdot N} \quad (12)$$

A random site  $x_i$  was occupied with probability

$$p(\sigma_i, T) = \min \left( 1, e^{-\frac{\phi_i(\sigma_i) - \Phi}{T}} \right) \quad (13)$$

where  $\phi_i(\sigma_i)$  is the marginal benefit cost ratio of site  $x_i$  and  $\Phi$  is the average benefit cost ratio of the present configu-

ration. The simulated annealing was performed in  $n$  steps with a new random subset of  $N \cdot \nu$  of the sites at each step. To satisfy the constraints, each step was followed by adding (removing) conserved sites starting with the sites of highest (lowest)  $\phi$  until the target value of  $\hat{U} = \lambda \cdot N$  was met. Temperature decay was exponential with decay parameter  $\tau$  per time step. Table 3 lists the parameter values used.

PARAMETER	CONNOTATION	VALUE
$T_0$	Start temperature	3
$\tau$	Decay parameter	0.001
$n$	Steps	3500
$\nu$	Fraction of sites	0.5

Table 3

Optimization parameters and standard values chosen for the simulated annealing

## 4. Analytical Bounds – Clusters and Disorder

Although the number of landscape configurations which fulfill the conservation target is extremely large, two structures occupy an outstanding position: One is a landscape where habitats are concentrated into one big cluster, the other where habitats are scattered randomly, disordered according to the lowest costs. Examples of these states will appear later in the results (Fig. 5). Clustering and disorder mark the two outer boundaries in terms of possible connectivity values: No other state produces more connectivity than a cluster, and no reasonable state (taking aside anti-correlated structures) produces less connectivity than the scattered, disordered state. It will prove useful for the interpretation of the results to derive some analytical properties of these two states.

### 4.1. Critical Values

Let us assume that agents can only choose between clustering and spread. Clustered structures lead to a higher certificate value per cell, but also to higher average costs per cell, because a spread, disordered configuration can more effectively concentrate conservation on the sites with the lowest costs. At low values of cost heterogeneity  $\delta$  compared to connectivity weight  $m$ , a clustered structure is clearly favored. At increasing cost heterogeneity, we expect a critical value  $\delta^c$  where the net benefits from clustering become smaller than the net benefits from spread.

We can derive this critical value by equating the worst benefit-cost ratio of cells within a cluster with the best ratio of an isolated cell. In a cluster, the habitats with the highest costs have  $c = 1 + \delta$ , while outside the cluster, the cells with lowest cost have  $c = 1 - \delta$ . The ecological value of a clustered and a disordered cell is given by eqs. 10 and 11. Hence, we have

$$\frac{1}{1 + \delta_{\text{add}}^c} = \frac{1 - m}{1 - \delta_{\text{add}}^c} \Rightarrow \delta_{\text{add}}^c = m/(2 - m) \quad (14)$$

$$\frac{1 + m}{1 + \delta_{\text{mar}}^c} = \frac{1 - m}{1 - \delta_{\text{mar}}^c} \Rightarrow \delta_{\text{mar}}^c = m \quad (15)$$

as critical values for additive and marginal certificates, respectively.

#### 4.2. Clustered and disordered cost level

Further, we are interested in the costs of maintaining the land at either of the two states. Let  $c_p(\zeta)$  denote the inverse cumulative distribution of the chosen probability density function of local costs. In economic terms, this can be regarded as the marginal cost function  $c_p(\zeta)$  of conservation. With costs being distributed uniformly across the interval  $[1 - \delta \dots 1 + \delta]$ ,  $c_p(\zeta)$  is given by

$$c_p(\zeta) = (1 - \delta) + 2\delta\zeta. \quad (16)$$

Cells in a cluster have 8 neighbors and therefore yield an ecological value of 1 per cell (eq. 4). Therefore, a number of  $\lambda \cdot N$  patches meets the regulatory target of an ecological value of  $\lambda$  per cell (eq. 5). As costs are uncorrelated, the mean costs  $\bar{c}_p$  within a cluster are approximately equal to the mean costs of the landscape (for the chosen function  $\bar{c}_p = 1$ ) as long as finite size effects can be neglected. Thus, the societal costs of reaching the target of a value  $\lambda$  per cell by means of a cluster are

$$C_{\text{clu}} = \frac{1}{N} \cdot \int_0^1 c_p(\zeta) d\zeta \cdot N \lambda = \lambda. \quad (17)$$

In the disordered state of density  $\alpha$ , where occupied sites are distributed randomly according to the lowest costs, each occupied cell has on average  $8 \cdot \alpha$  neighbors, leading to an average certificate value of  $(1 - m) + m \cdot \alpha$  per grid cell. To reach a target of  $\lambda$  per cell, we require that

$$\alpha \{(1 - m) + m \cdot \alpha\} = \lambda \quad (18)$$

which leads to

$$\alpha = \frac{-1 + m + \sqrt{(-1 + m)^2 + 4m\lambda}}{2m}. \quad (19)$$

The societal costs in the disordered state become

$$C_{\text{do}} = \alpha \int_0^\alpha c_p(\zeta) d\zeta = \alpha \cdot (1 - (1 - \alpha) \cdot \delta) \quad (20)$$

with  $\alpha$  given in eq. 19. The two cost curves for the clustered and the disordered state mark an upper boundary for cost-effective configurations. As a function of  $\delta$ , they intersect at

$$\delta = \frac{\alpha - \lambda}{\alpha - \alpha^2} = m \quad (21)$$

which coincides with the critical point for marginal certificate values (eq. 15).

## 5. Simulation Results

### 5.1. Critical Values

Scanning the parameter space of  $m$  and  $\delta$ , we observe steep transitions of all aggregated state variables along a curve of critical values  $\delta^c$  when moving from large to low ratios of  $m$  over  $\delta$ . Parameter values beyond this curve lead to disordered landscape structures, while values below  $\delta^c$  lead to ordered, connected structures. As expected, the shape of the transition line differs for additive and marginal certificate values. Fig. 5 shows the simulation results for additive (a.1) and marginal (a.2) certificates at  $\lambda = 0.1$  together with the analytically derived curves eqs. 14 and 15. The right side of Fig. 5 shows a vertical cross-section of the latter plots in  $\delta$ -direction at  $m = 0.5$ . The transition values  $\delta^c$  in this curve agree with the theoretical values from eqs. 14 and 15 (Table 4).

The introduction of coordination (submodel b.1 and b.2) leaves these results largely unchanged. Fig. 6 shows that coordination only slightly increases the tail after the transition point, but does not change the transition point. In contrast to the steep transitions of local decision processes, submodel (c) with cooperative decisions shows a rather linear transition for the same parameter values.

MODEL	SIMULATION	THEORY
Additive Value	$0.33 \pm 0.02$	0.33
Marginal Value	$0.50 \pm 0.02$	0.5

Table 4

Critical value  $\delta^c$  (measured as  $\delta$  at half transition) at  $m = 0.5$  from Fig 5 together with theoretical expectations

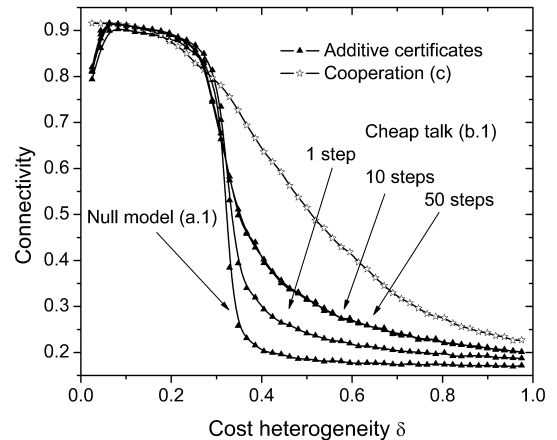


Fig. 6. Connectivity (on the y-axis) as a function of cost heterogeneity  $\delta$  at a fixed  $m = 0.5$ . It can be seen that increased communication does not affect the critical point  $\delta^c$  of the additive certificate curves.

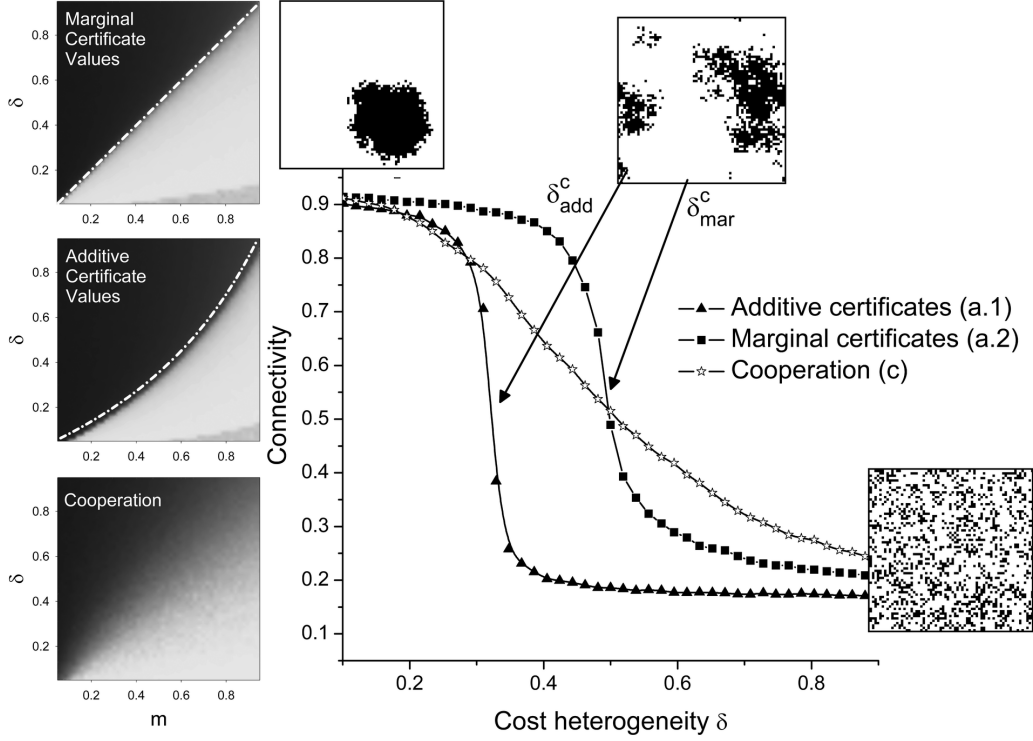


Fig. 5. On the left, landscape connectivity for marginal certificates (top), additive certificates (middle) and cooperation (bottom) as a function of cost heterogeneity  $\delta$  and connectivity weight  $m$  at  $\lambda = 0.1$ . Darker colors indicate lower connectivity. Dotted lines display the theoretical curves as given in eq. 14. The right graph shows a cross-section of the three plots in  $\delta$  direction at  $m = 0.5$  together with typical landscape structures emerging from the simulations in the three domains: Clusters (left), transition states (middle) and disorder (right).

## 5.2. Cost-effectiveness

One major question was how the three options would perform in terms of costs necessary to reach the conservation target. Figure 7 shows the societal costs as a function of the cost heterogeneity  $\sigma$  at  $m = 0.5$ , together with the theoretical cost levels for the clustered and the disordered state as calculated in eqs. 17 and 20 (dotted lines). Noticeably, the cost function of additive certificates displays a hump around the transition area (Fig. 7), leading to approximately 20% higher costs for additive compared to marginal certificates. When considering the theoretical cost functions for the ordered and the disordered state (eqs. 17, 20), the reason becomes evident: Marginal certificate values switch from clustering to disorder right at the intersection of the cost lines (eq. 21). In contrast, additive certificates switch already at a lower cost heterogeneity  $\delta$ . Here, the cost level of a disordered configuration is still higher than of a clustered one, resulting in efficiency losses in this area.

## 5.3. Coordination and cooperation

The inefficiency which has been observed for additive certificates is to a great extent mitigated by the introduction of coordination (Fig 8). For a value of 10 communication steps per trading period, only small differences

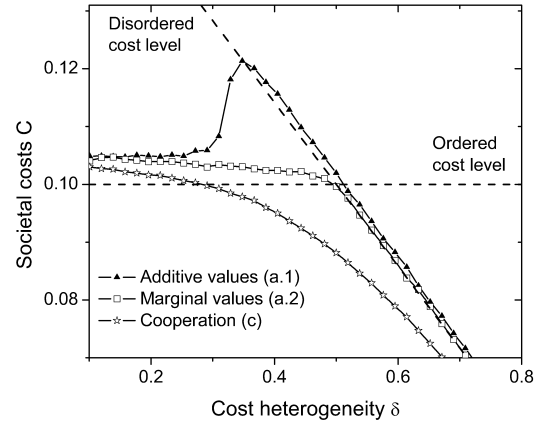


Fig. 7. Societal costs as a function of cost heterogeneity  $\delta$  at  $m = 0.5$  and  $\lambda = 0.1$  (solid lines) together with theoretical costs for the clustered and the disordered state (dashed lines).

between additive and marginal certificates remain. This results mainly from a better adaptation of land use to the current costs. Transition points and thus the landscape structure remain largely unchanged by coordination as discussed on Fig. 6.

Not surprisingly, the societal costs under cooperation are



considerably lower than for the other options (Fig. 7). They differ mostly around the critical values  $\delta_c$  where local decisions (submodel a and b) are more difficult than for extreme values of  $\delta$  where one allocation pattern (cluster or disorder) is clearly favored.

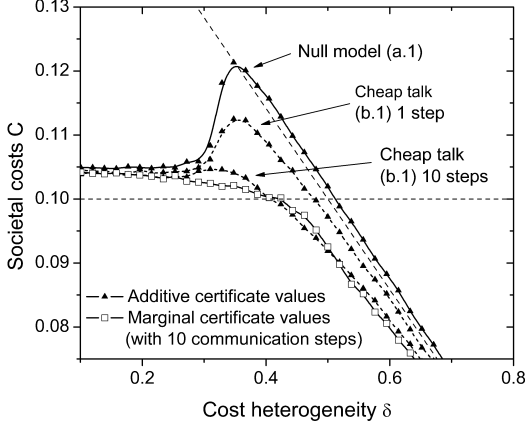


Fig. 8. Effect of coordination: The societal costs are plotted as a function of cost heterogeneity  $\delta$  at  $m = 0.5$  and  $\lambda = 0.1$ . With increasing coordination steps, additive certificate costs approach the costs of marginal certificates.

## 6. Discussion

### 6.1. Main findings

We have introduced a simple model of a market for tradable conservation services with spatially correlated certificate values. The model enabled us to compare different spatial certification rules such as additive and marginal certificate values and different types of agent behavior, including local and global decision processes. We found that local decision structures (null model a.1,a.2 and coordination b.1,b.2) lead to a partition of the parameter space in two areas with very distinct landscape patterns, divided by a small transition area. These predominant states are a completely clustered state, appearing when cost heterogeneity  $\delta$  is low compared to the connectivity weight  $m$ , and a completely disordered state, emerging when  $\delta$  is high compared to  $m$ .

The reason for the stability of these states in a dynamical and heterogeneous cost background lies in the fact that, starting from one of them, agents repeatedly end up in a very similar configuration since trading stops as soon as a local cost optimum is found. Even in the case of coordination with unlimited communication steps, agents stop trading once trade cannot improve the position of any single agent (Fig. 6). This limits the possibility of finding more complicated allocation patterns in a highly stochastic environment and explains the confinement of

simulation outcomes merely to the clustered or the disordered state as described above. In contrast, simulations of coordinating agents (submodel c), as an example of a global decision process, generate the whole range of intermediate clustering throughout the parameter space. Although not presented here, we checked that temporal and spatio-temporal correlation of costs generated by a random walk algorithm may also smooth out the steepness of the transitions in favor of more linear shapes. The reason is that when cost correlation length is large compared to the ecological correlation length, the chance of getting stuck in a local minimum is rapidly decreasing.

Cost differences between the different submodels arise most evidently in the transition regime, where connectedness becomes just as beneficial as spread. Here, additive certificates lead to a suboptimal level of landscape connectivity and result in increased societal costs. The origin of these cost differences lies in the different spatial incentives of both options: Additive certificates assign a part of the spatial benefits of a site to its neighbors and therefore give less incentive for clustering from the individual viewpoint. Yet, the strong costs increase can be predominately explained by losses due to misinformation. At increased rates of coordination, cost differences between additive and marginal certificates decrease strongly.

A more efficient allocation of conserved sites can only be reached through cooperation where the configuration space is explored in a way which avoids getting stuck in local minima. However, this requires landowners to reveal their true costs and temporarily accept lower payoffs if the group payoff is increased in exchange. Payments between landowners (side payments) could compensate for these losses, but it is an open question how this kind of cooperative system should be organized and if it is stable against exploitation by defectors and free-riders. Moreover, it is not clear whether defection can be detected. If agents can estimate the cost of neighboring landowners, defection is directly detectable and it seems reasonable that mechanisms such as reputation and social norms are strong enough to facilitate cooperation (Fehr and Schmidt, 1999; Sigmund et al., 2001; Milinski et al., 2002). However, if defection is only indirectly detectable, much weaker support is present for cooperation to hold (Sell and Wilson, 1991).

Concluding, we believe that the general problem of including spatial interactions into a local value function is largely independent of the exact shape of the ecological benefit function. Consequently, these results will qualitatively hold true for a wide range of ecological systems with spatial interactions. However, one dimension has been neglected in this simulation: Time, both on the ecological side (turnover, recreation times of habitat) as well as on the economic side (time preferences of humans) will be of major importance for a structurally realistic model of a conservation market. An extension of the model to a

market which includes space and time for evaluating conservational value should therefore be considered for future research.

## 6.2. Policy implications

Tradable permit markets for biodiversity present a promising policy instrument when local conservation cost are not known and flexibility and adaptation are of importance. However, it is too short-sighted to assume that giving the right exchange rate to a service such as biodiversity conservation will automatically lead to efficient allocations of conservation efforts. To find robust market designs, what is needed are realistic simulations incorporating both ecological and socio-economic aspects down to the individual landowner level at which important processes take place. Although we have shown that marginal certificates perform better than additive ones, considerations which are beyond the scope of this paper might still favor the latter in practice. As an example, marginal benefits might be considered unfair by landowners because payoffs depend on the order of trading. In the end, markets must not be judged by the standards of a first-best world, but by practice in the field, where other policy options also cause severe efficiency problems. If beneficial social structures are present, such as a strong tradition of cooperation and good management capacities, markets for biodiversity may be superior to other instruments, while under different circumstances, other policies like taxes may be more successful.

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